FINAL REPORT

Quantifying the risk of fire-facilitated transition to non-forest in California and the Southwest

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Abbreviations

AUC: Area under the [receiver operating characteristic] curve

BRT: Boosted regression tree

CBI: Composite burn index

CMD: Climatic moisture deficit

CMIP5: Coupled model intercomparison project phase 5

DISS: Dissection index

ET: Evapotranspiration

EVI: Enhanced vegetation index

FIA: Forest Inventory and Analysis

FRAMES: Fire Research and Management Exchange System

FRI: Fire return interval

GIS: Geographic information systems

GCM: Global climate model

GEE: Google Earth Engine

NDMI: Normalized differenced moisture index

NDVI: Normalized difference vegetation index

PRS: Percent replacement severity

RBR: Relativized burn ratio

RCP8.5: Representative concentration pathway – radiative forcing=8.5 W/m^2

SRAD: [Potential] solar radiation

TPI: Topographic position index

Key Words

California, Arizona, New Mexico

Burn severity, fire severity, stand-replacing fire, high-severity fire

Fire regime, fire return interval, fire frequency

Forest, trailing edge forest, type conversion, conversion to non-forest

Climate analog model, climate, climate change

Abstract

As wildfire activity increases in the western US due to warmer and dryer conditions, managers are increasingly concerned about fire-facilitated transitions from forest to non-forest. Concerns are heightened in California and the Southwest, regions that are currently being affected by increased fire activity, and where fire exclusion and historic forest management activities have led to unnaturally dense vegetation and abundant ladder fuels in some forest types. As such, this study was intended to quantify risk of fire-facilitated transition from forest to non-forest in California, Arizona, and New Mexico. To do so, we compartmentalized our study into three modules reflecting the incremental nature of our approach.

The first is the 'climate module', in which we developed and implemented an approach to assess potential climate-induced changes in vegetation and fire regimes over broad spatial scales. The climate module, however, assumes that changes in climate, whether gradual or abrupt, result in immediate changes to vegetation and fire regimes; this assumption is strained given that climate-mediated changes in vegetation are often delayed and require the catalyst of disturbance. Consequently, the 'disturbance module' was developed to characterize the drivers of and map the potential for stand-replacing fire as a disturbance agent. The 'climate and disturbance module' applied the methods from the climate module and incorporated stand-replacing fire from the disturbance module to evaluate the potential for fire-facilitated conversion to non-forest.

Results from the climate module indicate that vegetation patterns and fire regime characteristics (i.e. fire frequency and severity) and will likely shift in response to climate change. We revealed a potential climatic tipping point in which small changes in climate may result in conversion from forest to non-forest. In terms of fire regime characteristics, we show that universal increases in fire frequency and severity should not be expected; both increases and decreases in fire frequency and severity are projected and depend on the bioclimatic context. However, results from the climate module should only be interpreted as a longer range projection (*at least* 50-100 years) since disturbance as a catalyzing agent was not considered.

The disturbance module reveals that fuel and fire weather are the most important factors driving stand-replacing fire, though fuel was on average 1.7 times more influential than weather across our study area. Geospatial layers depicting the probability of stand-replacing fire were produced in the disturbance module and are available for download. In turn, these maps were used in the climate and disturbance module to characterize the potential for fire-facilitated conversion to non-forest. The climate and disturbance module shows that 4.3% of forest in the southwestern US is at risk of fire-facilitated conversion to non-forest when assuming fire burns under average weather conditions. When assuming that fire burns under extreme weather conditions, 30% of forest is at risk of conversion to non-forest.

In conducting this study, we delivered numerous in-person and web-based presentations to land managers and other interested parties (e.g. non-governmental organizations) in the southwestern US and elsewhere. We also delivered several presentations at professional conferences and published our results in peer-reviewed scientific journals. The mapped fire severity predictions (and metadata) we produced in the disturbance module are available online for download. See Appendix B for a full accounting of our science delivery.

Objectives

The overarching goal of this project was to quantify risk of fire-facilitated transition from forest to non-forest in California, Arizona, and New Mexico and was proposed in response to the following task statement: 'Implications of changing fuels and fire regimes – selected regions'. Our working hypothesis had two primary components: 1) there are bioclimatic settings where forests are at risk of conversion to non-forest, and 2) stand-replacing fire is an important catalyst when considering fire-facilitated transition to non-forest (i.e. low-severity fire is not likely to result in type conversion). Consequently, sites that met both of these criteria were considered at risk of fire-facilitated conversion to non-forest in the context of this study.

Several interrelated yet sequential objectives were proposed to achieve our overall goal:
1. For each of several tree species, identify the relationships between regeneration potential and its controlling factors (e.g. climate).
2. Estimate the expected fire severity (were a fire to occur).
3. Quantify risk of fire-facilitated conversion to non-forest and associated shifts in fire regime characteristics.
4. Evaluate how a warming climate will affect the ability of species to regenerate.
5. Evaluate management strategies that will reduce the risk of fire-facilitated transition to non-forest.

To reiterate, our overarching goal was to quantify risk of fire-facilitated transition from forest to non-forest in California, Arizona, and New Mexico. We initially intended to achieve this goal by using information on tree seedling establishment (i.e. regeneration), as stated above (objective 1). However, due to various issues such as uncertainty in our initial regeneration model, we instead focused on direct estimates of forest conversion, as described below. Furthermore, some objectives were not met across the entirety of the study domain due to difficulty obtaining FIA data (e.g. California). Despite these limitations, we successfully attained the goal of identifying areas at elevated risk of fire-facilitated conversion to non-forest for forests in Arizona and New Mexico.

To facilitate presentation and interpretation of our study, we organize various objectives and components into three study 'modules'. The remainder of this report is structured around these modules.
1) **Climate module:** We developed and implemented a methodology to estimate potential changes in vegetation and fire regimes under a warming climate in California, Arizona, and New Mexico. This module used the relationship between vegetation and climate and the relationship between fire regimes and climate to estimate change.
2) **Disturbance module:** We modelled and mapped the probability of stand-replacing fire in California, Arizona, and New Mexico.
3) **Climate and disturbance module:** We applied the novel methods from the climate module and incorporated stand-replacing fire from the disturbance module to evaluate the potential for fire-facilitated conversion to non-forest in the southwestern US.

Background

As wildfire activity increases in the western US due to warmer and drier conditions, managers are increasingly concerned about fire-facilitated transitions from forest to non-forest. How forests will respond to fire and whether trees will be able to regenerate and persist is unclear, especially as a warming climate will limit the moisture required for successful tree regeneration (Dodson and Root, 2013). Concerns are especially heightened in California and the Southwest, regions that are currently being affected by severe and long droughts, and where fire exclusion and historic forest management activities have led to unnaturally dense vegetation and abundant ladder fuels in some forest types (e.g. dry forests) (Stephens 2005). Many of these forests historically burned with low to moderate severities but are now theorized to be more susceptible to uncharacteristically severe wildfire (e.g. Moore et al. 2004); evidence suggests this is indeed the case (Mallek et al. 2013). Fire-facilitated transitions may have alarming consequences in terms of region-wide forest composition and future fire regimes. Managers need to anticipate whether, and where, forests are likely to convert to non-forest after wildfire. This is particularly important under climate change since a warming climate will influence both the prevalence of stand-replacing fire and the ability of trees to persist.

Climate clearly has a strong influence on the geographic distribution of vegetation and fire regimes (Stephenson 1990, Krawchuk et al. 2009, Parks et al. 2014b), and consequently, climate change would be expected to shift these distributions (Lenihan et al. 2003, Flannigan et al. 2009). In this context, it is important to recognize that vegetation patterns and fire regimes are intrinsically coupled, in that climate-induced changes to fire regimes will result in vegetation shifts, and vice versa (Keane et al. 2015). Yet, most pertinent studies to date evaluate the response of either vegetation or fire to climate change, but rarely evaluate both. Furthermore, whereas many studies have examined potential climate-induced changes in area burned or fire frequency, very few have explicitly evaluated how *fire severity* would be expected to change under a warming climate. Public land managers would benefit from studies that recognize and explicitly evaluate the intertwined nature of fire and vegetation; they would also benefit from a greater understanding of how fire severity patterns may be expected to shift under climate change.

This said, studies involving the potential effect of climate change on vegetation and fire generally do not account for what has been referred to as plant-climate disequilibrium. That is, vegetation does not track precise fluctuations or trends in climate because mature plants have adaptive traits that allow them to resist stresses of extreme climate. Mature trees, in particular, can survive and persist under substantial inter-annual and decadal fluctuations in climate. At regional to continental scales, this suggests that climate change will not necessarily result in immediate changes to the distribution of forests. This phenomenon of plant-climate disequilibrium must be considered when evaluating potential shifts from forest to non-forest. Under disequilibrium conditions, disturbances such as wildland fire play a critical role, in that it can catalyze abrupt vegetation change under a warming climate (Turner 2010, Crausbay et al. 2017). For forests, this catalyzing influence is most likely with stand-replacing fires (i.e. low-severity fires will not generally result in conversion to non-forest). Consequently, having a clear

understanding of where stand-replacing fire is likely to occur would inform our understanding of fire-facilitated conversion to non-forest.

We posit that forests that are most vulnerable to fire-facilitated conversion to non-forest are located along the warm and dry edge of forest biome boundaries (e.g. low elevation and southern periphery); these sites are considered trailing edge forest. Sites within these zones that are also susceptible to stand-replacing fire substantially increase the risk of type conversions, and as such, are particularly vulnerable to transition to non-forest (Savage et al. 2013). Placing an emphasis on stand-replacing fire in climatically stressed forests (i.e. the trailing edge) will provide managers a better understanding of the risk of fire-facilitated conversion to non-forest.

The climate module

We developed and implemented a methodology to estimate potential changes in vegetation and fire regimes under a warming climate. To estimate change, this module used the relationship between vegetation and climate and the relationship between fire regimes and climate. This module does not explicitly account for disturbances that may influence the distributions of vegetation. The peer-reviewed version of this study focused on "mountainous ecoregions of the western US" (Parks et al. 2018a). Here, we focus on the states of California, Arizona, and New Mexico.

METHODS

In this module, we use maps characterizing baseline vegetation, fire regime characteristics, and climate to make projections about future vegetation and fire regimes. We obtained gridded maps of vegetation and fire regime characteristics for California, Arizona, and New Mexico from the Landfire program (Rollins 2009). Specifically, we reclassified the biophysical setting vegetation layer from Landfire into five broad classes representing mesic forest, cold forest, dry forest, grassland/shrubland, and sparse/barren. In terms of fire regime characteristics, we used Landfire's mean fire return interval (FRI) and percent replacement severity (PRS). The vegetation and fire regime products used here are intended to represent the "historical" time period (circa 1700-1900) and are hereafter referred to as the baseline period. Our main goal is to evaluate how these baseline maps might be expected to change under a warming climate. To do so, we associate baseline vegetation and fire regime characteristics with baseline climate and then make projections using estimates of future climate.

We obtained gridded climate data (1-km resolution; 30-year climatic normals) from Wang et al. (2016) (available at https://adaptwest.databasin.org/). We used the earliest time period available (1961-1990) to represent the baseline climate. Future climate is represented by two time periods: 2041-2070 (hereafter 2055 or mid-century), and 2071-2100 (2085 or late-century). Future climate projections are based on an ensemble of 15 CMIP5 GCMs under the RCP8.5 emissions scenario. We used two variables to represent baseline and future climate: Hargreaves' climatic moisture deficit (CMD; mm/yr) and Hargreaves' reference evaporation minus climatic moisture deficit (hereafter evapotranspiration [ET; mm/yr]). These are simplifications of the two variables typically used to characterize the water balance (climatic water deficit and actual

evapotranspiration, respectively) and are related to temperature and precipitation (amount and timing).

Projections of future vegetation and fire regimes were produced using a *climate analog model*. A climate analog model, as applied here, assumes that the future vegetation and fire regime characteristics for each location (i.e. pixel) are currently represented at other locations within the study domain. Because we have an estimate of the *future climate* for any given pixel, we can identify the locations within the study domain that have a similar climate under the *baseline period*. The climate analog model assumes that the vegetation and fire regime characteristics of those locations will represent the future vegetation and fire regime characteristics for a pixel of interest (Fig. 1). Analogous climates were defined as those that were ±47 mm/yr for CMD and ±38 mm/yr for ET; see Parks et al. (2018a) for rationale and further details. We used the three nearest pixels to inform our model; specifically, we used the mean FRI and PRS and the majority of the vegetation type of the three nearest analogous pixels. Using this approach, we produced maps of vegetation and fire regime characteristics for future time periods (i.e. mid- and late-century) which we compared to baseline period maps produced by Landfire. Implicit in this approach is the well-supported assumption that climate is a strong driver of both vegetation and fire regimes (Stephenson 1998, Lutz et al. 2010, McKenzie and Littell 2017).

Figure 1. For each pixel in our study area (e.g. green star), we characterize the *future* climate. We then identify locations in our study area that have a similar climate under the *baseline period* (1961-1990); these are climate analogs (black pixels). We then compare the vegetation and fire regime characteristics of the pixel of interest to that of the climate analogs, thereby allowing an evaluation of potential change.

To graphically illustrate potential shifts of fire regime characteristics, we fitted splines of FRI and PRS for the baseline and future time periods as a function of the climatic moisture deficit (CMD; baseline). This simple illustration depicts potential changes along one climatic gradient. Given the complexities of climate's direct and indirect influence on fire regimes, this illustration using a single climate variable is simply intended to show broad-scale biogeographic patterns.

RESULTS AND DISCUSSION

Projected changes in vegetation and fire regimes by mid- and late-century are evident but highly variable across the study area (Figs. 2 and 3). In California, for example, there is an apparent contraction of mesic and cold forest and an expansion of dry forest in the upper elevations of the

Figure 2. Baseline fire regime characteristics and vegetation (left column) for forests in California. Potential changes to these forests by mid- and late-century (middle and right column). Bar plot shows the relative area (for regions characterized as forest during the baseline period) of each vegetation type across the three time periods.

Sierra Nevada (Fig. 2). These vegetation shifts correspond to a decrease in fire return intervals (i.e. increased fire frequency) and a decrease in fire severity, likely reflecting the often inverse relationship between fire frequency and severity in forested ecosystems (Keane et al. 2002). Interestingly, the boundary between the Central Valley and the surrounding mountains exhibits an apparent shift from dry forest to non-forest (see the "bathtub ring" in Fig. 2). In these areas, fire intervals are generally expected to increase and severity is projected to increase. In southern California, most of the forested area under baseline conditions is expected to shift to non-forest, with associated changes to fire regimes.

Projected changes to vegetation and fire regimes are also evident in Arizona and New Mexico (Fig. 3). Over half of the area characterized as dry forest under baseline conditions is projected to convert to non-forest by late-century. It is important to note however, that this estimate assumes plant-climate equilibrium, which is a strained assumption, as described later in this section and elsewhere. Nearly all of the areas characterized as mesic or cold forest under baseline conditions are projected to convert to dry forest by late-century (Fig 3). Though highly variable, associated changes to fire return intervals are also expected. Fire severity is projected to increase across much of Arizona and New Mexico; this reflects associated changes to vegetation, in that the emerging vegetation types (shrubland, grassland, and pinyon-juniper) are more conducive to stand-replacing fire compared to the baseline vegetation.

Fire return interval (FRI) and percent replacement severity (PRS) for the baseline period, mid-21st century, and late-21st century vary along a gradient represented by the climatic moisture 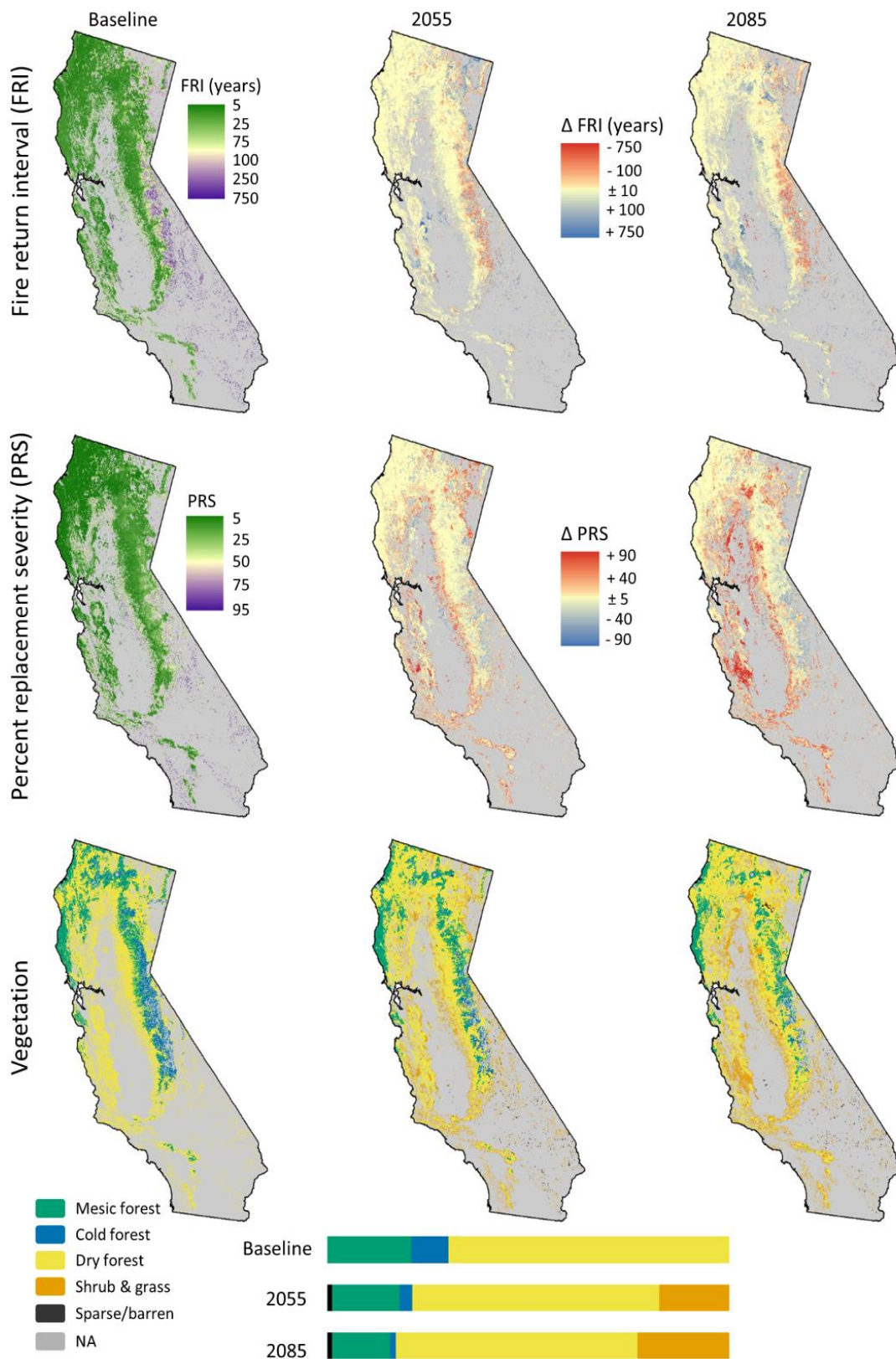deficit (CMD) (Fig. 4). All three time periods show a similar pattern where both FRI and PRS are highest at the extremes in CMD and are lowest at intermediate values (~500-625 mm/year). For locations with CMD values less than ~400 mm/year during the baseline period, FRI decreases in future time periods; at higher CMD values, FRI increases in the future. Percent replacement severity follows a similar pattern, decreasing in future time periods at lower baseline period CMD values and increasing at higher values (threshold = ~450 mm/year) (Fig. 4).

Fire regimes and vegetation will undoubtedly change in response to a warming climate. For the regions we investigated, we did not find a universal increase or decrease in fire return interval (FRI) or percent replacement severity (PRS); instead it appears that potential changes to fire regimes depend on the bioclimatic domain (McKenzie and Littell 2017). In wet regions (low CMD), for example, FRI and PRS are projected to decrease in the future, whereas dry regions may see an increase in FRI and PRS (Figs. 4 and 5). Our results also suggest that substantial changes in vegetation could accompany these climate-induced shifts in the fire regime, highlighting important interactions and feedbacks associated with climate, fire, and vegetation (Schoennagel et al. 2009). In particular, the expected increase in FRI and PRS at intermediate moisture conditions (climatic moisture deficit [CMD] = ~500-625 mm/yr) suggest a tipping point that could have important implications for vegetation. This CMD range generally coincides with the lower limit for many forests (Fig. 5 & Stephenson 1990) that may be especially susceptible to drought and a corresponding state transition to shrubland/grassland (cf. Breshears et al. 2005).

Our approach implicitly assumes that there is equilibrium among climate, fire, and vegetation; this assumption implies that fire regimes and vegetation will keep pace with changing climate. Although this is a common assumption in many climate change studies involving vegetation and fire, lags in the response of vegetation often result in *disequilibrium*. Plant-climate disequilibrium occurs when changes in climate do not immediately result in changes to fire regimes and vegetation (Svenning and Sandel 2013). Consequently, explicitly incorporating disturbances that may catalyze changes to vegetation would improve future assessments (e.g. see climate and disturbance module).
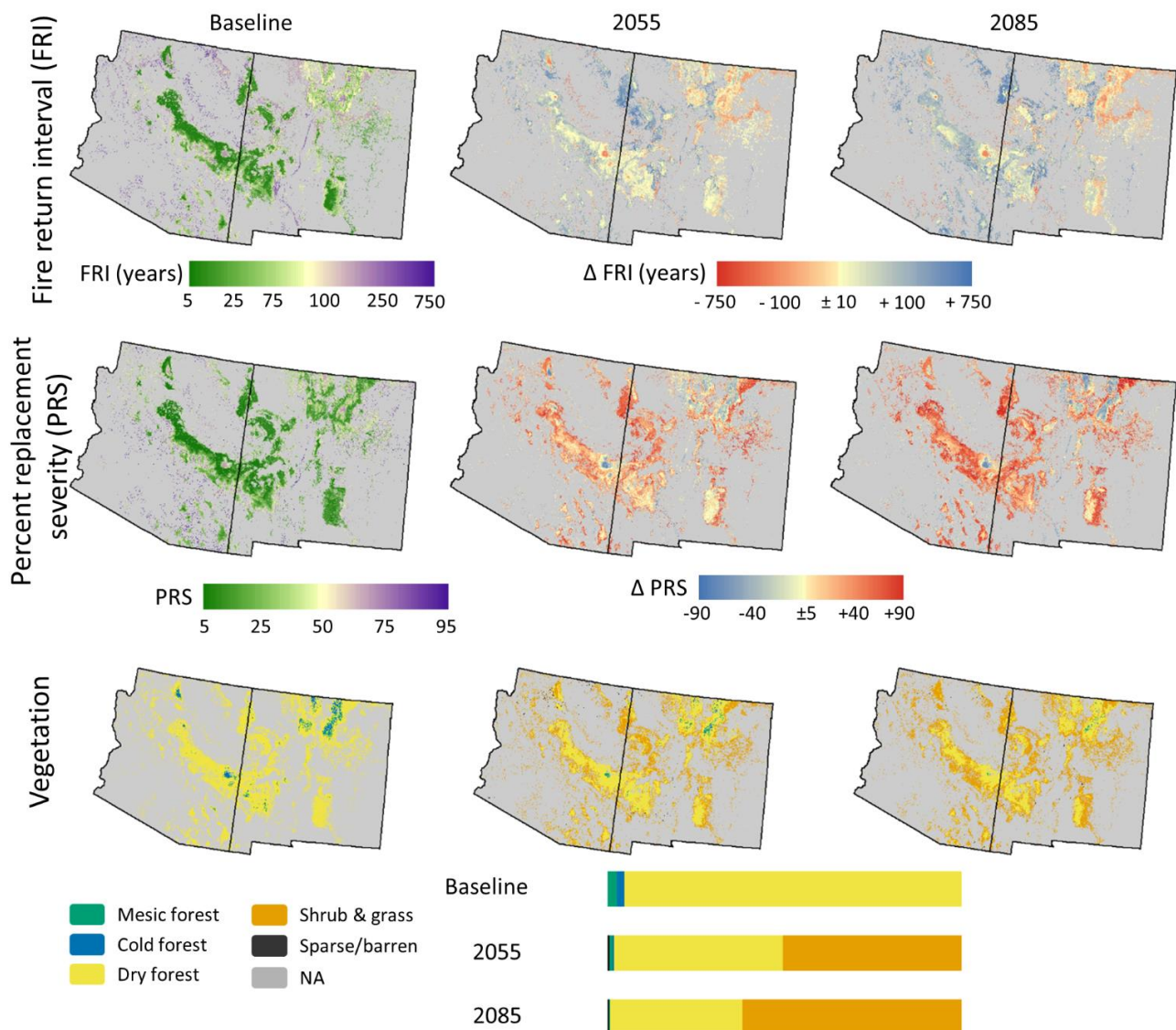
Figure 3. Baseline fire regime characteristics and vegetation (left column) for forests in Arizona and New Mexico. Potential changes to these forests by mid- and late-century (middle and right column). Bar plot shows the relative area (for regions characterized as forest during the baseline period) of each vegetation type across the three time periods.
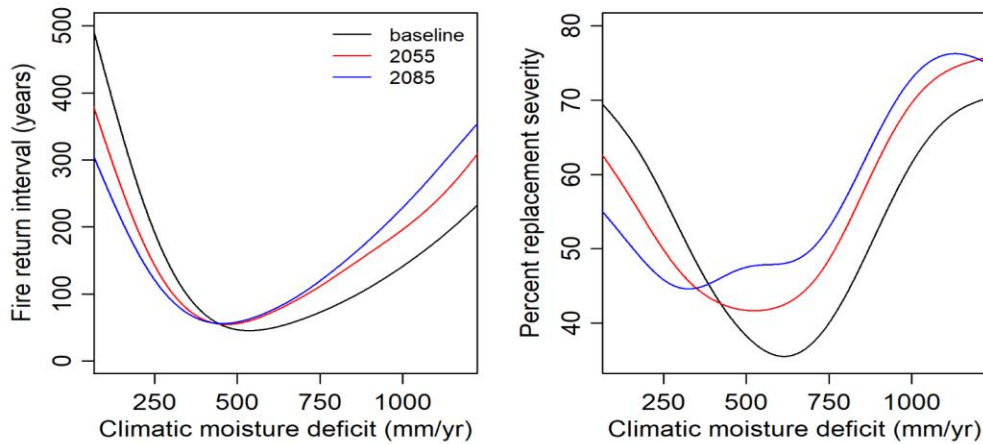
Figure 4. Fitted splines describe (left) the fire return interval (FRI) and (right) percent replacement severity (PRS) for baseline and future time periods as a function of the climatic moisture deficit (CMD). The climatic moisture deficit (x-axis) is static and is representative of the baseline climate (1961–1990). These figure were built using data from all mountainous ecoregions in the western US and are described at length in Parks et al. (2018a).
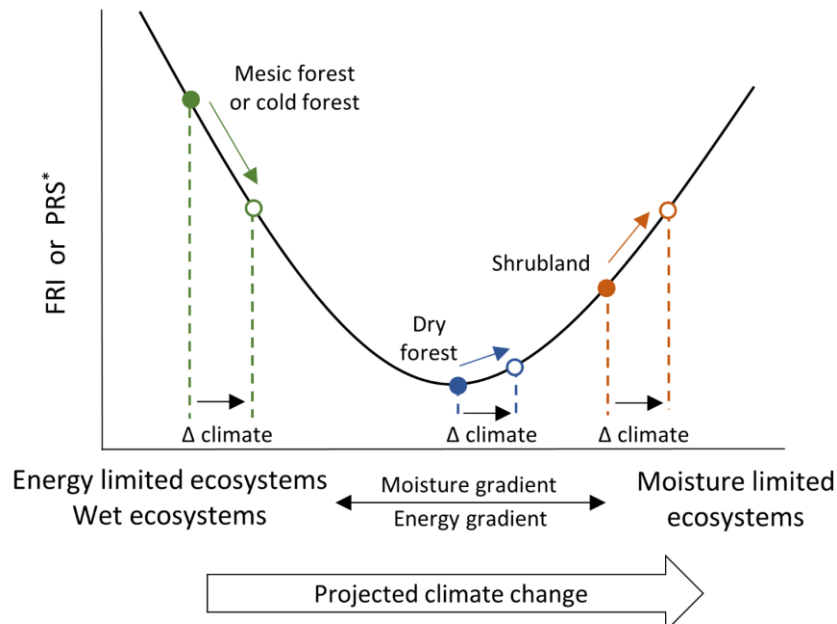
Figure 5. Conceptual model describing projected climate-induced shifts in fire return interval (FRI) and percent replacement severity (PRS) along a resource gradient representing moisture and energy. As the climate warms, mesic forests and cold forests are expected to experience decreased FRI and PRS. Dry ecosystems, such as shrubland/grassland, are expected to experience increased FRI, which is likely in response to decreased productivity and available biomass. Dry forests, especially those on the ecotone between forest and non-forest, are predicted to experience increased FRI and PRS, which may be an indication of transition from forest to non-forest (or from ponderosa pine to pinyon-juniper). This conceptual model was built using data from all mountainous ecoregions in the western US and is described at length in Parks et al. (2018a).

The disturbance module

In the disturbance module, we modelled and mapped the probability of stand-replacing fire. The peer-reviewed version of this study focused on "fire-prone ecoregions of the western US" (Parks et al. 2018b). Here, we focus here on ecoregions that intersect the states of California, Arizona, and New Mexico.

METHODS

Fire has the potential to catalyze shifts to non-forested states. Consequently, we built a statistical model describing stand-replacing fire for each fire-prone ecoregion that intersects California, Arizona, and New Mexico (Fig. 6). Fire severity was measured using the relativized burn ratio (RBR), a satellite index (resolution = 30-m) that differences pre- and post-fire Landsat imagery. The RBR has a high correspondence to field-based measures of severity such as the composite burn index (CBI) (Parks et al. 2014a). We classified the RBR data into binary categories representing stand-replacing fire (RBR ≥ 298) and other severity (RBR < 298). This threshold was based on a CBI value of 2.25, which corresponds to ≥ 95% canopy mortality (Miller et al. 2009). A similar thresholding approach was also used by Dillon et al. (2011). Satellite imagery used to generate RBR was obtained from the Monitoring Trends in Burn Severity program (MTBS) (Eidenshink et al. 2007), which distributes Landsat data for fires ≥400 ha that occurred since 1984.

We evaluated 16 explanatory variables in the model for each ecoregion which can be categorized into four groups representing live fuel, topography, climate, and fire weather. The fuel group comprises three satellite vegetation indices: NDVI, NDMI, and EVI. These indices were generated using pre-fire imagery distributed by MTBS. NDVI is an index of vegetation productivity and biomass. NDMI is a measure of vegetation moisture. EVI is alternative index of vegetation productivity that may be better suited to high biomass regions (Huete et al. 2002). These three metrics are sensitive to changes in amounts and distribution of live fuel over time due to vegetation growth, disturbance, and drought and implicitly incorporate management activities and disturbances such as fuel reduction treatments and wildland fire. Inclusion of 'static' fuel metrics such as vegetation type or cover (e.g. www.landfire.gov) (cf. Birch et al. 2015) were not considered since such products are only updated periodically and are thus not sensitive to annual dynamics. The inclusion of dynamic fuel metrics allows for annual updates of the fire severity predictions while accounting for temporal variability in fuel.

Topography is represented by four variables (resolution = 30-m): dissection index (DISS), topographic position index (TPI), potential solar radiation (SRAD), and slope (Slope). DISS is a measure of roughness. TPI is a measure of valley bottom vs. ridge top and was calculated at the 2-km scale. SRAD incorporates slope, aspect, and topographic shading and is a measure of insolation. Slope is a measure of steepness. These particular topographic variables have been linked to fire severity (Dillon et al. 2011, Birch et al. 2015), although they likely represent indirect processes that drive fire severity. For example, solar radiation (SRAD) may indirectly affect fire severity through its influence on productivity and fuel moisture.

Climate is represented by three variables (resolution=1-km): climatic moisture deficit (CMD), reference evapotranspiration minus CMD, hereafter referred to as evapotranspiration (ET), and mean summertime temperature (June through August) (T.sm). These variables represent climate normals over the 1981-2010 time period (i.e. they do not vary annually) and were obtained from Wang et al. (2016) (available at https://adaptwest.databasin.org/). CMD and ET are broadly representative of the climatic water balance (climatic water deficit and actual evapotranspiration, respectively) (Stephenson 1998) but are simplifications because they exclude factors such as soil water holding capacity and wind speed in their calculations. These climate variables are likely indirect measures of fuel amount and vegetation type through their effect on productivity (Krawchuk et al. 2009, Garbarino et al. 2015). Nevertheless, variables such as these have been identified as strong predictors of wildland fire.

1. East Cascades
2. Klamath
3. Sierra Nevada
4. California North Coast
5. California Central Coast
6. California South Coast
7. Southern Rockies
8. Colorado Plateau
9. Arizona-New Mexico Mountains
10. Apache Highlands
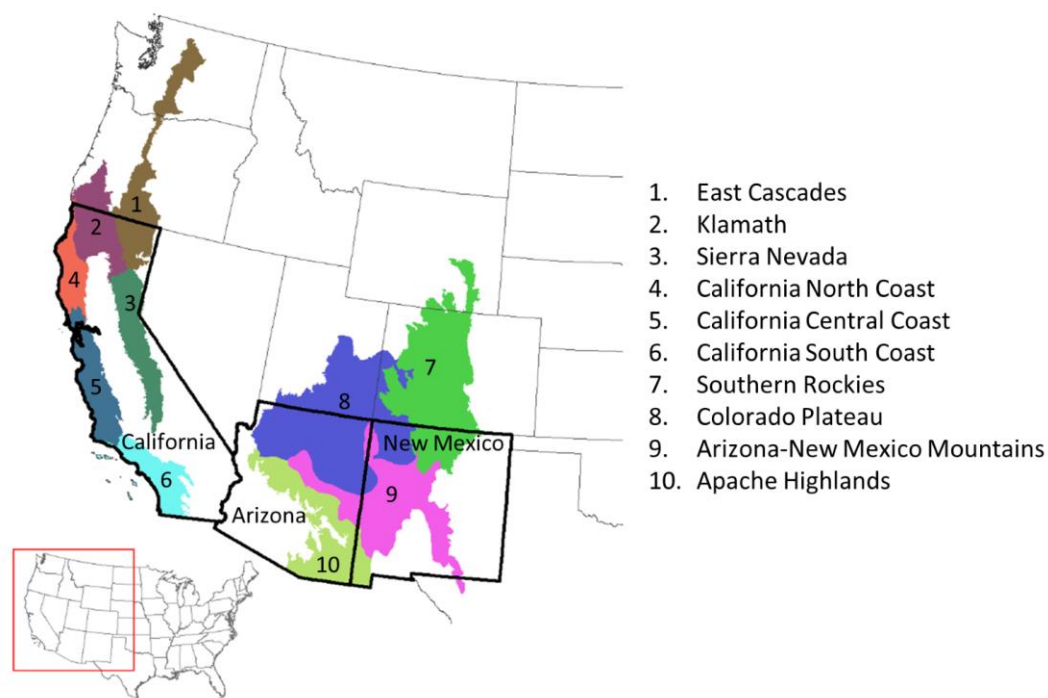
Figure 6. We modeled the probability of stand-replacing fire in these fire-prone ecoregions that intersect California, Arizona, and New Mexico.

The fire weather group includes six gridded variables, three of which represent daily variability (e.g. daily maximum temperature) and three of which represent annual variability (mean temperature for any given year). Our choice to use two temporal resolutions in characterizing fire weather is a result of research that has elucidated the importance of both daily and annual fire weather in driving fire severity (Abatzoglou et al. 2017, Keyser and Westerling 2017). The daily gridded fire weather variables (resolution=4-km) include burning index (BI.day), energy release component (ERC.day), and maximum temperature (Tmax.day). BI.day is related to the potential flame length and ERC.day is a metric of the potential energy released at the head of a spreading fire. BI.day and ERC.day were calculated as described by Preisler et al. (2016). Tmax.day was obtained from Abatzoglou (2013). Annual fire weather variables (resolution=1-km) include heat

moisture (HM.ann), mean temperature (Temp.ann), and climatic moisture deficit (CMD.ann). These variables represent the year in which any given fire occurred and were generated using the ClimateNA software package (version 5.10) (Wang et al. 2016).

We sampled individual 30-m pixels within fires that occurred from 2002-2015. We only sampled pixels identified as forest (i.e. forest, woodland, and savanna). We removed all pixels <100 m from the fire perimeter to reduce edge effects common at fire boundaries. All analyses and predictions were conducted using the native resolution of the response variable (30-m). For each ecoregion, we used boosted regression trees (BRT) using the 'gbm' package in R to model stand-replacing fire (binary response) as a function of live fuel, topography, climate, and fire weather.

The relative importance of variable groups was calculated using the AUC (area under the curve) of a five-fold cross validation using a process that excluded all variables from a particular group. Specifically, we compared the five-fold cross validated AUC of the full model to models that iteratively excluded all variables representing live fuel, topography, climate, and fire weather. The specific equation was as follows:

$$Relative\ influence_i = \frac{AUC.full - AUC.no.var_i}{\sum_{i=1}^{i=4}(AUC.full - AUC.no.var_i)} \times 100$$

Where *AUC.full* was the AUC of the full model, *AUC.no.var* was the AUC of the model excluding any particular variable group, and *i* represented one of the four variable groups.

From these BRT models, we produced wall-to-wall raster maps depicting the probability of stand-replacing fire, if a fire were to occur, for each ecoregion in which the cross-validated AUC ≥0.70. We did not want to produce maps with a high degree of uncertainty; therefore we opted not to produce maps for an ecoregion if the model AUC was less than 0.70. For the fuel inputs (NDVI, NDMI, and EVI), satellite imagery from 2016 spanning the entirety of each ecoregion was obtained using Google Earth Engine (GEE; https://developers.google.com/earth-engine/). Consequently, these raster predictions represent fairly current fuel conditions across each ecoregion. Predictions theoretically range from zero to one and depict the probability of stand-replacing fire.

The mapped predictions are intended to represent the expected fire severity under average weather conditions in which fires burn. This is somewhat challenging, however, given that weather is spatially and temporally dynamic. Consequently, we produced 100 initial predictions and varied the weather for each; all other inputs across each ecoregion (fuel from 2016, topography, and climate) were held static. To vary the weather, we randomly selected 100 records from our fire severity datasets. Each record represents one burned pixel with a unique combination of observed daily and annual fire weather. We used the observed fire weather from each random record for each of the 100 initial predictions. We then averaged the 100 initial predictions over each 30-m pixel, resulting in one raster map depicting the probability of stand-replacing fire under average weather conditions in which fires burn. An important consideration here is that the severity predictions do not represent "average weather conditions", but the

"average weather conditions *under which fires burn"*. That is, because fires often burn under more extreme fire weather, our predictions implicitly incorporate weather associated with high fire activity.

For those ecoregions in which the relative influence of fire weather ≥15%, we produced two additional raster maps, one depicting the probability of stand-replacing fire under conditions representing moderate weather and the other under conditions representing extreme weather. To do so, we calculated the 50th and 95th percentile *for each pixel* out of the 100 previously described initial predictions. While these maps represent the 50th and 95th percentile in predicted outcomes for each pixel, we use them to represent the outcomes of moderate and extreme fire weather, respectively. Neither map says anything specific about the percentile of weather conditions under which they occurred, but they can be interpreted as resulting from moderate and extreme fire weather.

To illustrate how our models can potentially be used to monitor changes in the probability of stand-replacing fire due to fuel treatments, we made pre- and post-treatment predictions using the BRT model from the Arizona – New Mexico Mountains ecoregion. We obtained imagery representing the live fuel for the years 2007 (pre-treatment) and 2011 (post-treatment) using Google Earth Engine. Again, we produced two sets of predictions for each time period (pre- and post-treatment) representing moderate and extreme fire weather, as previously described.

RESULTS AND DISCUSSION

We incorporated data from over 1000 fires across the ecoregions in California, Arizona, and New Mexico to describe and explain the probability of stand-replacing fire. On average, the models performed moderately well for the 10 ecoregions (Table 1). The average spatially and temporally independent cross-validated AUC statistic was 0.73 and ranged from 0.67 (Sierra Nevada) to 0.81 (Colorado Plateau).

Although there was substantial variation across ecoregions (Table 1), live fuel was the most important variable group, with an average relative influence of 49.3% among ecoregions; this ranged from 5.1% (California North Coast) to 75.0% (AZ-NM Mountains). This finding provides valuable insight pertaining to the ongoing debate as to whether fuel or fire weather are more important in driving fire severity (cf. Thompson and Spies 2009). Whereas some studies found fuel was more important (e.g. Fang et al. 2015), others concluded weather was more important (e.g. Bradstock et al. 2010). We found that live fuel was 1.7 times (on average) more influential than fire weather across the 10 ecoregions. This finding is not trivial in terms of management efforts to reduce fire severity because land managers can control fuel via fuel treatments, prescribed fire, and managed wildland fire (formerly termed wildland fire use) but cannot control fire weather.

Table 1. Cross-validated AUC and the relative importance for each of the four groups of variables used to model the probability of stand-replacing fire in fire-prone ecoregions that intersect California, Arizona, and New Mexico. The relative importance across all groups sums to 100% for each ecoregion.

Region ID	Ecoregion name	Cross-validated AUC	Relative importance			
			Live fuel	Topography	Climate	Weather
1	East Cascades	0.68	60.7	12.4	5.6	21.2
2	Klamath	0.68	38.8	25.0	0	36.2
3	Sierra Nevada	0.67	58.7	15.7	19.1	6.5
4	California North Coast	0.70	5.1	19.6	9.1	66.2
5	California Central Coast	0.73	64.6	22.3	13.1	0
6	California South Coast	0.72	40.6	9.4	0	50.1
7	Southern Rockies	0.72	57.4	12.5	22.9	7.3
8	Colorado Plateau	0.81	39.0	6.9	2.1	52.0
9	Arizona-New Mexico Mountains	0.79	75.0	0.2	9.7	15.0
10	Apache Highlands	0.75	53.3	1.0	9.9	35.9
	AVERAGE	**0.73**	**49.3**	**12.5**	**9.2**	**29.0**

Fire weather was the second most influential variable group (avg. relative importance = 29.0%), ranging from 0% (California Central Coast) to 66.2% (California North Coast). Previous studies have reported somewhat conflicting findings pertaining the relative influence of fire weather in driving fire severity. Whereas some studies found weather to be moderately to highly influential (e.g. Lydersen et al. 2017), others found that the influence of weather was marginal to negligible (e.g. Harris and Taylor 2015). Although our results show that weather was less influential in driving stand-replacing fire than fuel, its influence was important in most ecoregions and should not be discounted in terms of managing fuel and fire.

Topography was the third most influential variable group (avg. relative importance = 12.5%). This finding contradicts nearly every fire severity study to date that showed topography has a moderate to high influence on fire severity (e.g. Holden et al. 2009, Dillon et al. 2011, Fang et al. 2015, Kane et al. 2015, Birch et al. 2015, Estes et al. 2017). We posit that topography is an indirect measure of fuel, and that because we directly account for fuel (using satellite-derived vegetation indices), topography is deemed a relatively unimportant factor. It is worth noting that many of these previously mentioned studies do not incorporate any measure of fuel or vegetation into their analyses (Holden et al. 2009, Dillon et al. 2011, Kane et al. 2015), and consequently, the influence of topography may be unintentionally elevated. For example, even though Dillon et al. (2011) found topography to be the strongest driver of severity across large regions of the western US, they clearly stated that topography was serving as a proxy for variation in fuel and bioclimatic variables (i.e. fuel moisture and temperature) which were not accounted for in their study. Since we capture such variability in live fuel using satellite-derived vegetation indices, the influence of topography on its own is diminished.

Overall, climate was the least influential variable group (avg. relative importance = 9.2%; Table 1). This contrasts with some previous studies. For example, Kane et al. (2015) found that climate was highly influential in driving fire severity in the Sierra Nevada. However, we suspect that climate was less important in our study because, over broad spatial and temporal extents,
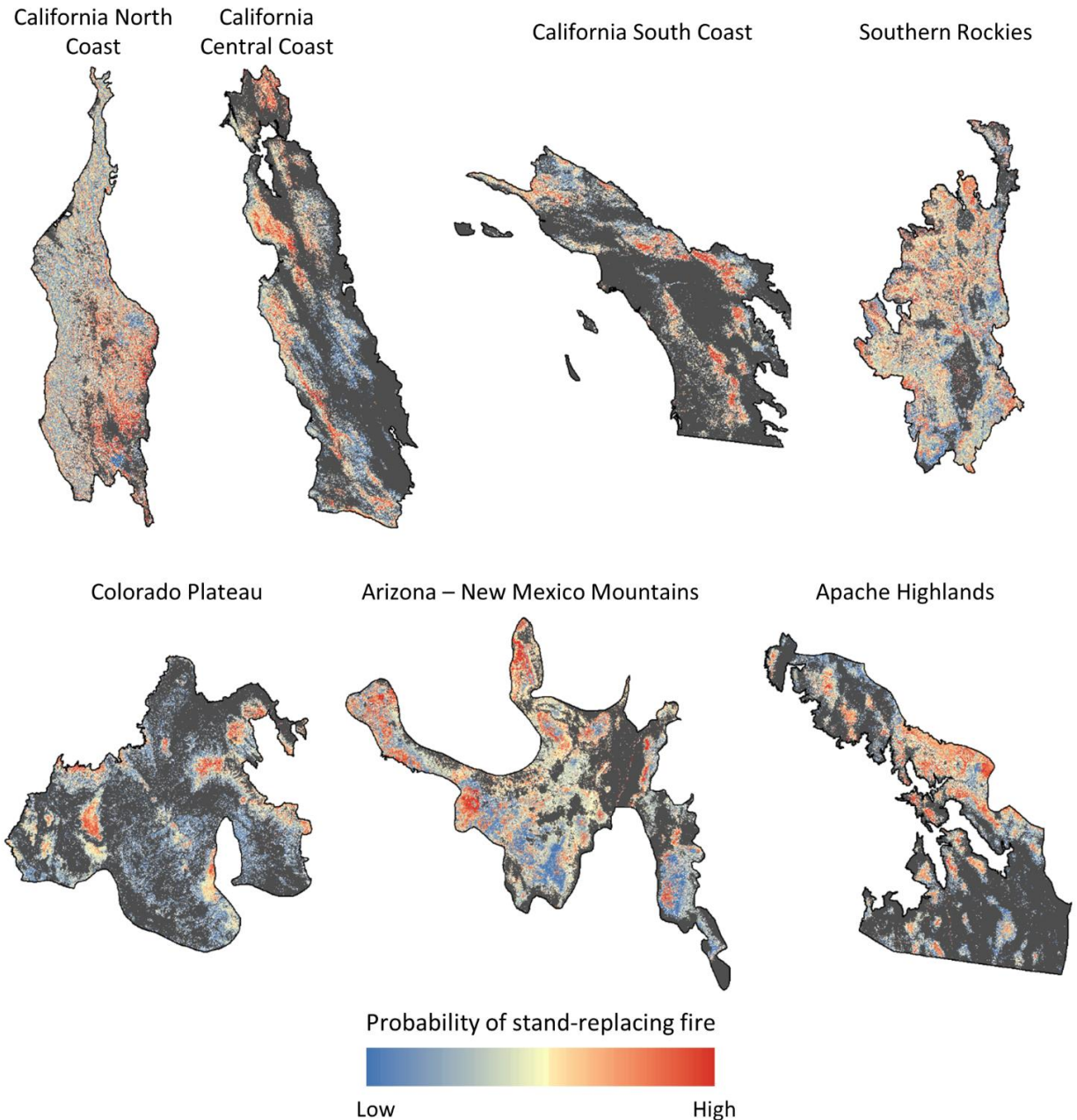
Figure 7. Maps depict the probability of stand-replacing fire (were a fire to occur) for fire-prone ecoregions intersecting California, Arizona, and New Mexico (see Fig. 6). These GIS-friendly predictions can be downloaded from: www.frames.gov/NextGen-FireSeverity.

climate provides an indirect measure of fuel associated with inherent biophysical environments. We suggest, as do others (Miller and Urban 1999), that climate may indirectly represent factors that were not well accounted for by our variables. Specifically, we believe that climate may correspond to dominant vegetation type, in that climate promotes particular physiognomic vegetation types and species that are more or less susceptible to fire. For example, cooler and wetter climates are more likely to support species that are more susceptible to fire-induced mortality (e.g. Engelmann spruce), whereas warmer and drier climates are more likely to support species that can survive fire (e.g. ponderosa pine) (Lutz et al. 2010).

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Raster maps depicting the probability of stand-replacing fire were built for the seven ecoregions in which the cross-validated AUC ≥0.70 (Fig. 7). These gridded probabilities represent fuel conditions (i.e. as measured with Landsat imagery) in 2016 and average weather conditions under which fires burn and show substantial spatial variability in the probability of stand-replacing fire. For ecoregions in which the relative importance of weather ≥15% (n=3), we produced two additional raster maps depicting the probability of stand-replacing fire under conditions representing moderate and extreme fire weather; these additional maps are not shown here but can be viewed in Parks et al. (2018b). All mapped severity predictions can be downloaded in a GIS-friendly format through the Fire Research and Management Exchange System (FRAMES; www.frames.gov/NextGen-FireSeverity).

Maps of pre- and post-treatment predictions provide an example of how our models and approach can potentially be used to quantify and monitor changes in the probability of stand-replacing fire due to fuel treatments (Fig. 8). This example shows that, under conditions representing both moderate and extreme fire weather, there is an overall reduction in the probability of stand-replacing fire within treatment units.

Managing for wildfire has become incredibly complex as we face the nexus of increasingly large and intense wildfires, more frequent drought, landscapes with heavy fuel accumulations due to prolonged fire exclusion, and a rapid expansion of the wildland-urban interface. Land management agencies have a daunting challenge to reduce risks from fire to communities and fire fighters while simultaneously restoring forests to more resilient conditions (https://www.forestsandrangelands.gov). In response, land management agencies in the US established a long-term fuel reduction program in which millions of hectares have been treated since 2001 using a variety of methods such as mechanical thinning and prescribed burning. Various efforts are underway to assess how to best focus such fuel reduction activities given that land management agencies have limited resources. In particular, spatially explicit planning frameworks have offered an effective means to prioritize treatments across landscapes (e.g. Ager et al. 2016). These planning frameworks are often built on spatial assessments of quantitative wildfire risk that incorporate the probability of wildfire occurrence across a range of simulated fire intensities, and the effects of fire on specific values at risk (e.g. natural resources, built assets) (Scott et al. 2013). We suggest that the modeling framework in this study could complement these efforts and allow predictions of stand-replacing fire to be integrated with fire occurrence and behavior predictions to provide managers with a more comprehensive set of risk-analysis information to target locations in wildfire mitigation planning.
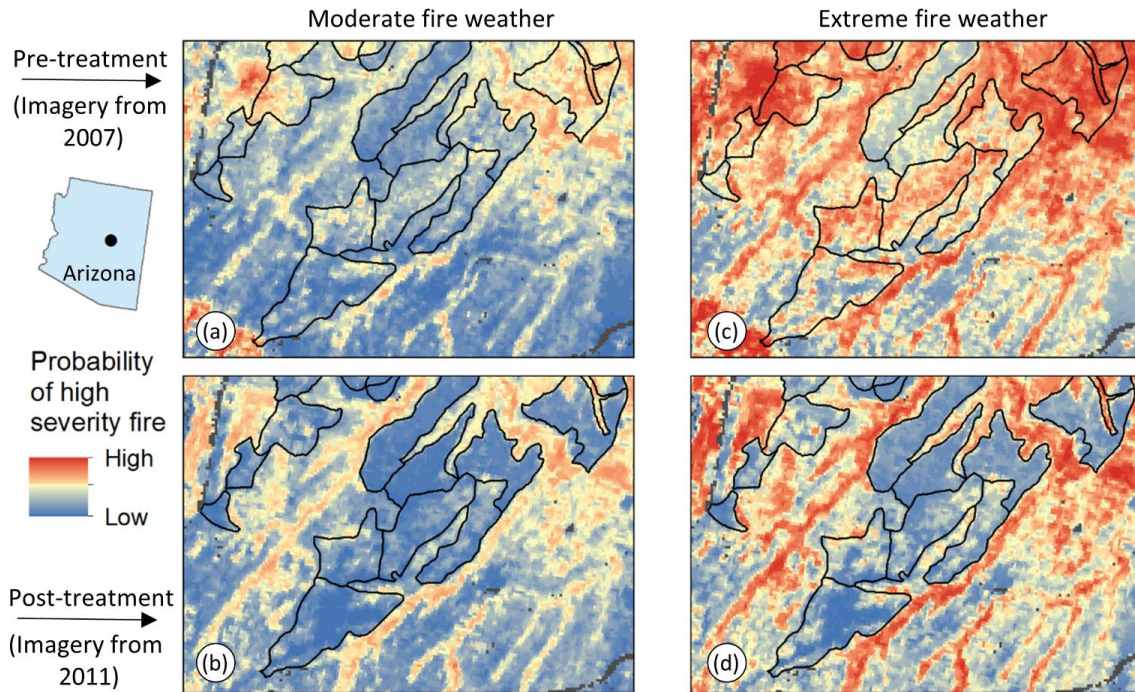
Figure 8. Example shows pre-and post-treatment predictions (top and bottom row, respectively) of the probability of stand-replacing fire under moderate (*a, b*) and extreme (*c, d*) fire weather on the Apache-Sitgreaves National Forests, Arizona, USA. Fuel treatment units are represented by the solid black outlines. All fuel treatments are commercial thinning that occurred in 2010 or 2011.

The climate and disturbance module

We applied the novel methods from the climate module and incorporated stand-replacing fire from the disturbance module to evaluate the potential for fire-facilitated conversion from forest to non-forest in the southwestern US. The peer-reviewed version of this study focused on the intermountain western US (Parks et al. 2019). Here, we focus here on fire-prone ecoregions that intersect the states of Arizona and New Mexico.

METHODS

The overall objective of this module was to evaluate the potential for fire-facilitated conversion from forest to non-forest in the southwestern US by mid-21st century. We explicitly incorporate the influence of both climate change and fire as a catalyst vegetation change in this evaluation. We identified areas that are currently climatically suitable for forest but are projected to become climatically unsuitable. We consider these areas to be trailing edge forests. We then identify those trailing edge forests that also have a high probability of stand-replacing fire and consider these to be at the highest risk for fire-facilitated conversion to non-forest.

We first identified trailing edge forests; i.e. those areas that are currently climatically suitable for forest but are projected to become climatically unsuitable my mid-century. To do so, we integrated US Forest Service Forest Inventory and Analysis (FIA) data (Bechtold et al. 2005) with the previously described climate analog modelling. Specifically, we classified each FIA plot as either forest or non-forest. Each plot was then attributed with baseline (1981-2010) and mid-21st century (2041-2070) CMD and ET (these climate variables were previously described).

Focal pixel of interest (CMD=263 and ET=468 mm/yr *in mid-century*)

FIA plots that are ±1 mm (after square-root transformation) from the focal pixel of interest using *baseline climate*

All other FIA plots

Figure 9. Example of our methods that use climate analogs to evaluate the potential distribution of forest under a future climate. For each pixel within the study area (e.g. red star on map), we characterized the future climate (CMD and ET) as predicted in mid-century and then identified all FIA plots that had analogous climates (±1 mm after square-root transformation) under baseline conditions (1981-2010) (green dots). We compared the forest condition (forest/non-forest) at each focal pixel to that of the seven nearest FIA plots that were identified as climate analogs (e.g. green circles) using a majority rule. The focal pixel (red star) represents baseline forest condition (forest/non-forest) and the plots identified as climate analogs (green circles) represent potential mid-century forest condition.

To characterize the distribution of forest within the study domain under baseline conditions, for each 1-km pixel, we identified the seven nearest FIA plots with analogous climates under baseline conditions. If the majority of those plots were forest, we assigned the pixel as forest, whereas if the majority of those plots were non-forest, we assigned the pixel as non-forest. Analogous climates were defined as those that were ±1 mm/yr (after a square-root transformation) for CMD and ET; note this climate bin width is different than that described in the climate module. This procedure resulted in a map representing baseline forest.

To characterize the potential distribution of forest under a future climate, this procedure was repeated, but we first characterized each pixel with mid-century climate and then we identified those FIA plots with analogous climates under baseline climate (Fig. 9). This resulted in a map representing the potential distribution of mid-century forest. A comparison of the potential distribution of forest under baseline vs. mid-century climate allowed us to identify trailing edge forests. The choice to use ±1 mm CMD and ET (after square-root transformation) to define analogous climates and the seven nearest analogous plots to assign a pixel as forest/non-forest is described in detail in Parks et al. (2019).

We then intersected trailing edge forests with maps depicting a high probability of stand-replacing fire. The previously described maps describing the probability of stand-replacing fire (see the disturbance module) were resampled to 1-km resolution and converted to binary classes
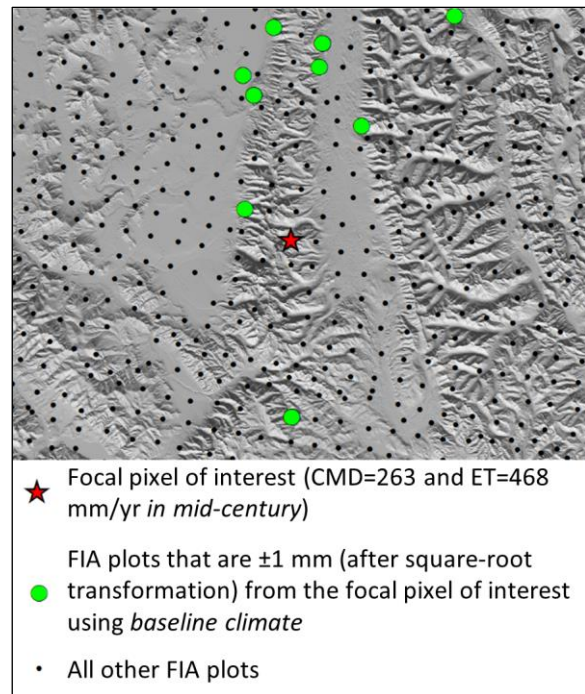
representing stand-replacing or other severity. These steps were conducted on maps depicting stand-replacing fire under both average and extreme weather conditions. To map areas with an elevated risk for fire-facilitated conversions to non-forest, we evaluated spatial coincidence between datasets that satisfied both of the following criteria: 1) pixels identified as trailing edge forest (i.e. climatically suitable for forest under baseline climate but climatically unsuitable for forest by mid-century), and 2) pixels with a high probability of stand-replacing fire. We consider areas meeting both criteria to be at elevated risk of fire-facilitated conversion from forest to non-forest.

RESULTS AND DISCUSSION

About 149,000 km^2 (41.7%) of the three ecoregions evaluated is mapped as forested under baseline climate conditions (Table 2). However, we identified over 73,000 km^2 (49.3%) of this area as trailing edge forest that will become climatically unsuitable to forest by mid-century (Fig 10).

Within trailing edge forest, ~6,400 km^2 is susceptible to stand-replacing fire under average weather conditions (Table 3, Fig. 11), and therefore meets our criteria for being at elevated risk of fire-facilitated conversion to non-forest. This area amounts to 8.7% of trailing edge forest extent and 4.3% of baseline forest in our study area. However, when we consider fire under extreme weather conditions, we find that nearly 45,000 km^2 of trailing edge forest is susceptible to stand-replacing fire and therefore is at elevated risk of fire-facilitated conversion to non-forest (Table 3). This represents ~61% of trailing edge forest and ~30% of all baseline forest in these ecoregions.

Table 2. Evaluation of baseline forest cover, trailing edge forest, and change in area climatically suitable for forest by mid-century.

Ecoregion name	Area forested (km^2): baseline	Area trailing edge forest (km^2)	Total reduction in area climatically suitable to forest by mid-century (km^2)[†]	Area of forest (% of ecoregion)	Area trailing edge forest (% of baseline forest)	Total reduction in area climatically suitable to forest by mid-century (% of baseline forest)[†]
Colorado Plateau	59,614	31,755	24,230	30.5	53.3	40.6
AZ-NM Mountains	60,520	27,085	23,193	52.6	44.8	38.3
Apache Highlands	29,016	14,693	9,463	34.8	50.6	32.6
TOTAL	149,150	73,533	56,886	41.7	49.3	38.1

[†]This includes both increases and decreases in area that is climatically suitable to forest.

Stand-replacing fire is not the only threat to trailing edge forests, as other disturbance agents also have the ability to catalyze shifts to non-forest. For example, severe drought can kill trees (Allen et al. 2010) and result in extensive forest die-off (Allen et al. 2015). Insects, often in conjunction with moisture stress, can also result in regional forest die-off (Breshears et al. 2005). Our study focused on a specific type of transition catalyzed by a single stand-replacing fire. Fires of moderate- to high-severity that occur at short intervals (< ~15 years between reburns) have also been shown to shift successional trajectories towards shrub and grass dominated systems (Coop et al. 2016,

Figure 10. Distribution of stable and trailing edge forest in the Colorado Plateau, Apache Highlands, and Arizona – New Mexico Mountains ecoregions.

Coppoletta et al. 2016). Consequently, our estimates of trailing edge forest area that is at elevated risk of abrupt conversion to non-forest should be considered conservative. These additional threats may be pronounced in our study are, as ~49% of forest in the Colorado Plateau, Arizona-New Mexico Mountains, and Apache Highlands ecoregions are considered trailing edge forests. Warming that is likely to occur beyond mid-century only exacerbates these threats.
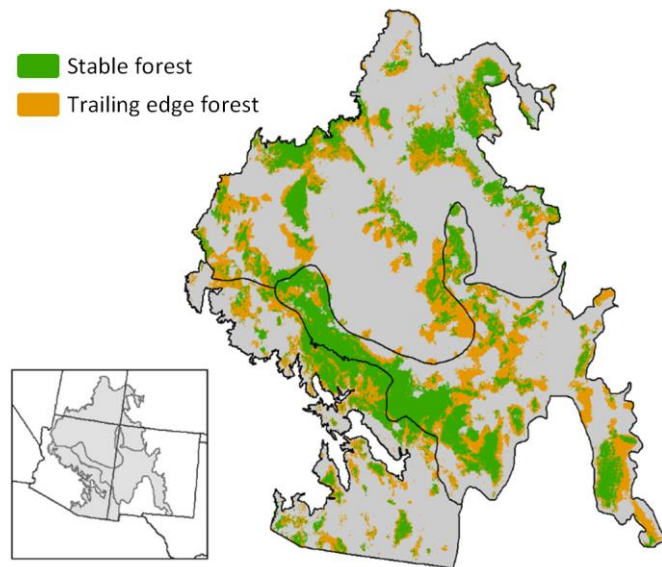
Land management agencies have several available options for reducing the potential for fire-facilitated type conversions and slowing forest loss. For example, forest restoration treatments such as prescribed fire and thinning are effective strategies to reduce the probability of stand-replacing fire (Safford et al. 2012); such treatments would be particularly relevant for drier, trailing edge sites that have that have been heavily impacted by fire suppression and historic logging operations. Given that fire severity tends to increase during years of extreme drought (Parks et al. 2018c), judiciously allowing naturally ignited fires to burn during non-drought years could also be a viable option for reducing fuel loads. Walker et al. (2018), for example, showed that sites with a restored fire regime were less likely to convert to non-forest than sites with altered fire regimes. This said, in cases where forests are substantially degraded, some studies have suggested that that fire should not be reintroduced without first applying treatments such as thinning (e.g. Allen et al. 2002). In the driest portions of the trailing edge forest or within designated wilderness and other protected areas, allowing nature to take its course (i.e. no management intervention) may be the most appropriate climate change response strategy. Resisting change, for example, by aggressively preventing and suppressing fire, could be considered a viable short-term strategy in locations with highly valued resources (e.g. municipal watersheds), but it has been suggested that such a strategy will not be successful in the long-run considering that directional climate change will ultimately cross ecological thresholds. Ultimately, a diverse portfolio of climate change response strategies could serve as a bet hedging

tactic in trailing edge forests given uncertainty in future disturbances, their interactions, and the associated ecological responses (Millar et al. 2007).
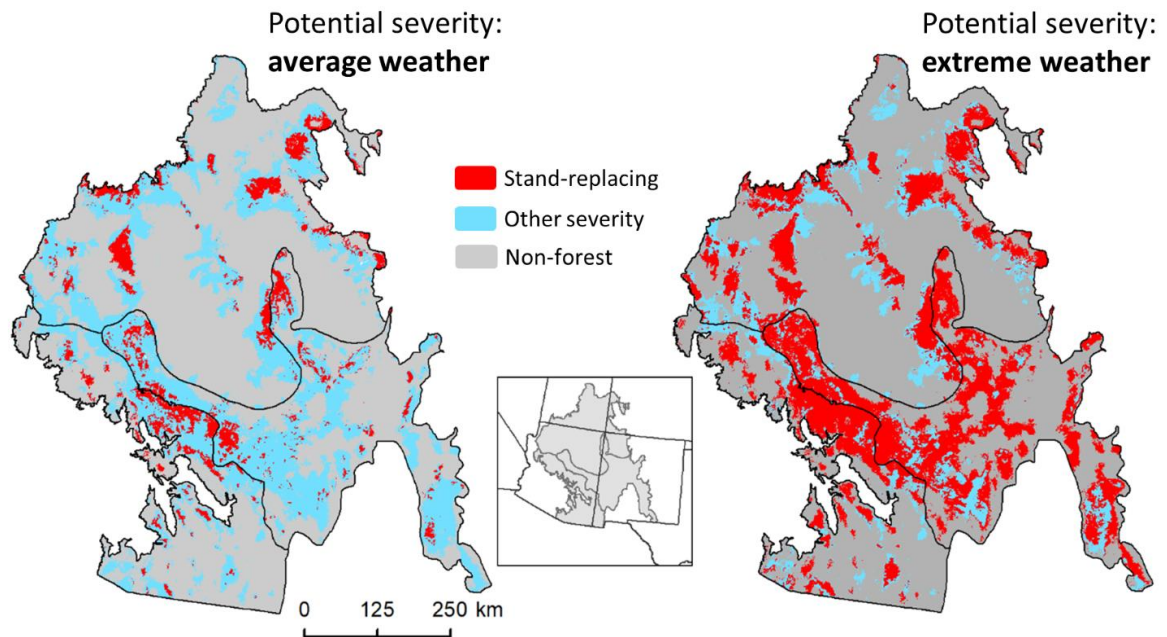
Figure 11. Maps depict the distribution of stand-replacing fire (were a fire to occur) under average and extreme weather in the Colorado Plateau, Apache Highlands, and Arizona – New Mexico Mountains ecoregions.

Table 3. Area of trailing edge forest affected by each fire severity class under average and extreme weather conditions.

Ecoregion name	Average weather predictions				Severe weather predictions			
	Other severity (km^2)	Stand-replacing (km^2)[†]	Other severity (% of baseline forest)	Stand-replacing (% of baseline forest)[†]	Other severity (km^2)	Stand-replacing (km^2)[†]	Other severity (% of baseline forest)	Stand-replacing (% of baseline forest)[†]
Colorado Plateau	29,129	2,626	48.9	4.4	19,845	11,910	33.3	20.0
AZ-NM Mountains	24,858	2,227	41.1	3.7	2,101	24,984	3.5	41.3
Apache Highlands	13,140	1,553	45.3	5.4	6,822	7,871	23.5	27.1
TOTAL	67,127	6,406	45.0	4.3	28,768	44,765	19.3	30.0

[†]These columns should be interpreted as the area and percent of forested area at risk of fire-facilitated conversion to non-forest. They represent pixels that are trailing edge forest and are at risk of stand-replacing fire under average and extreme weather conditions.

The spatial resolution of our analysis (1-km) does not capture finer resolution processes that would create heterogeneity in the risk of fire-facilitated conversion to non-forest. In particular, fire regime characteristics and vegetation (type and structure) are known to vary according to slope aspect and potential solar radiation. Also, the fire severity predictions we used in this study are contingent on a fire actually burning, yet we know the probability of burning varies widely according to factors such as fuel, ignitions, and topography. Future efforts that address fire-facilitated conversion to non-forest could therefore incorporate finer-scale controls on fire severity as well as fire probability maps (e.g. Short et al. 2016) to highlight regions with an elevated risk of conversion.

Science delivery

We published four peer-reviewed articles in scientific journals and delivered three oral presentations at professional conferences on various components of this project (Appendix B). Geospatial layers depicting the probability of stand-replacing fire were produced for a number of ecoregions (see the disturbance module) and are available for download from the Fire Research and Management Exchange System (FRAMES) (https://www.frames.gov/NextGen-FireSeverity). These geospatial datasets have also been added to the Forest Service ArcGIS Server: https://apps.fs.usda.gov/fsgisx01/rest/services/RDW_Wildfire/RMRS_NextGenerationFireSeverityMapping/ImageServer. In accordance with our Data Management Plan, metadata for these geospatial layers is housed at the Forest Service Research Data Archive.

In terms of direct interactions with managers, we delivered three presentations in New Mexico in September, 2018. These presentations summarized the overall findings of this study; audiences included students at New Mexico Highland University and the Santa Fe, Carson, and Gila NFs. The SW Fire Science Consortium assisted with facilitating and promoting these presentations. We also delivered a webinar titled 'Modelling and mapping the potential for stand-replacing fire in the Southwest and beyond' in October, 2018; this webinar was hosted and promoted by the Southwest Fire Science Consortium. We assisted the Rocky Mountain Research Station in producing a 'Science you can use' bulletin that was delivered to several thousand members of the land management community in 2018. Two 'Science spotlights' were produced for this study and are available on the RMRS website. Additionally, we were invited to deliver a presentation at the Southwestern Regional Watershed, Air, Ecology, Climate Change, and Invasive Species Workshop in Flagstaff, AZ (2017). At the Southwest Fire Ecology Conference (2016), we also held an informal roundtable discussion with approximately seven FS employees to solicit feedback on the project goals and preliminary results. Appendix B provides a full list of science delivery activities.

Key findings

Climate module

Vegetation and fire regimes in California, Arizona, and New Mexico are expected to change under a warming climate. The general trend is that current vegetation will transition to drier vegetation types, including conversions from forest to non-forest. In terms of fire regime characteristics, universal increases in fire frequency and severity should not be expected; some bioclimatic domains may experience more frequent fire whereas others may experience less frequent fire. Accordingly, some bioclimatic domains may experience higher severity fire whereas others may experience lower severity fire. These findings, however, are best interpreted as a long-range projection (i.e. *at least* 50-100 years) and short-term responses to climate change will likely differ from our results. This is because we implicitly assume that there is equilibrium among climate, vegetation, and fire regimes, meaning that changes in climate result in immediate and corresponding changes in both vegetation and fire regimes. This assumption is rarely realized. For example, although our models suggest that cold forests may shift towards dry forest conditions with different fire regime characteristics, it is not entirely realistic to assume, for example, that a mature lodgepole pine forest will transition to a mature dry mixed conifer forest in only a few decades. Consequently, our results should not be strictly interpreted in terms of the exact magnitude or timing of change. Instead, we emphasize the general direction of change as shown in the conceptual model (Fig. 5). Nevertheless, our findings suggest that there is a climatic tipping point at which vegetation transitions from forest to non-forest (Fig. 5); as the climate continues to warm, some dry forests may exceed this climatic threshold (CMD = ~500-625 mm/yr) and be susceptible to transition to a non-forested state. Explicit attention to disturbances that catalyze immediate change is necessary to better understand ecosystem trajectories, including the potential for conversion to non-forest.

Disturbance module

Our results show that live fuel and fire weather are the most important factors driving stand-replacing fire in the ecoregions we evaluated; on average, fuel was 1.7 times more important than weather. Topography and climate had a non-negligible influence but were overall much less important that fuel and weather. Our finding that topography was not highly influential contrasts with several previous studies. The ecoregional models we built allowed us produce "wall-to-wall" predictions depicting the probability of stand-replacing fire, were a fire to occur (Fig. 7). These geospatial data layers can be downloaded from the Fire Research and Management Exchange System (FRAMES; www.frames.gov/NextGen-FireSeverity). It is worth noting, however, that we did not produce said predictions for any ecoregion with a poor-performing model (i.e. some ecoregions in California). Nevertheless, these predictions can aid in prioritizing restoration treatments and identifying areas at risk of fire-facilitated conversion to non-forest.

Climate and disturbance module

We found that ~49% of total forest extent in the southwestern US may become climatically unsuitable to forest by mid-century and is therefore considered trailing edge forest in the context of this study (Fig. 10). Of the trailing edge forest, 8.7% (6,400 km^2) is susceptible to stand-replacing fire and therefore meets our criteria for being at elevated risk of fire-facilitated

conversion to non-forest. This estimate, however, assumes that fire will burn under average weather conditions. When we evaluate the potential for stand-replacing fire under extreme weather, we found that nearly 45,000 km^2 of trailing edge forest is at elevated risk of fire-facilitated conversion to non-forest (Table 3). This represents ~61% of trailing edge forest and ~30% of all baseline period forest in these ecoregions.

Implications for management

Recognizing that a warming climate will alter both vegetation and fire regimes is an important management consideration in the forests of California, Arizona, New Mexico, and beyond. Perhaps the most consequential of these potential changes is evident in dry forests along the ecotone between forest and non-forest (e.g. Fig. 5). In such areas, future climate conditions will be more conducive to shrubland or grassland vegetation, suggesting that conversions to a non-forested state are possible and even probable. For example, we interpret the inflection point (see Figs. 4 and 5) as a threshold or tipping point at which small shifts in climate may result in conversion from forest to non-forest. However, it is also important to recognize that some transitions to non-forest may not be realized, at least in the near-term, unless there is a disturbance catalyst that removes the living trees in these regions near the climatic tipping point.

We focused on stand-replacing fire as a disturbance catalyst; one of our main goals was to quantify the drivers of such fire. We found that live fuel and fire weather were the main factors controlling stand-replacing fire, though fuel was about 1.7 times more influential than weather. This is an important finding in terms of managing dry forested landscapes across our study domain: land managers can control fuel via fuel treatments and prescribed fire, but they cannot control fire weather. This suggests that, if managers are interested in reducing fire-facilitated conversion to non-forest in regions characterized by dry forest, efforts to modify fuel to reduce the probability of stand-replacing fire could be appropriate. This said, the influence of fire weather was fairly strong and should not be discounted. Although managers cannot control weather, they do have some control over the weather conditions in which fires burn through decisions pertaining to fire suppression. For example, aggressive fire suppression during less-than-extreme weather conditions may be a lost opportunity to reduce fuels and the probability of stand-replacing fire during future fire events.

We define trailing edge forest and those areas that are currently forest but will have a climate more suitable to non-forest (i.e. shrubland/grassland) in future decades. When intersecting trailing edge forest with regions that are susceptible to stand-replacing fire under extreme weather conditions, we found that ~45,000 km^2 of forest in the area analyzed is at risk of fire-facilitated conversion to non-forest. This is obviously an extremely large area that will challenge the retention of forests and associated ecosystem services in the southwestern US and beyond. To respond to this challenge, we posit that a diverse portfolio of response strategies (*sensu* Millar et al. 2007) is necessary and could serve as a bet hedging tactic in the management of trailing edge forests. For example, forest restoration treatments such as prescribed fire and thinning are effective strategies to reduce the probability of stand-replacing fire and therefore the risk of conversion to non-forest. Resisting change, for example, by aggressively preventing fire from

occurring, could be considered a viable short-term strategy in locations with highly valued resources (e.g. municipal watersheds), but it has been suggested that such a strategy will not be successful in the long-run considering that directional climate change will ultimately cross ecological thresholds. In the driest portions of the trailing edge forest or within designated wilderness and other protected areas, allowing nature to take its course (i.e. no management intervention) may be the most appropriate management response strategy.

The models and maps we produced that depict the probability of stand-replacing fire potentially have other uses for management that were not directly utilized in this study. For example, our models and the resulting predictions could potentially serve as a performance metric for evaluating hazardous fuel treatments (see Fig. 8). Although the US Forest Service often uses "acres treated" as a performance measure, this measure does not capture whether treatment objectives have been met (USDA Forest Service 2016). Specifically, the primary objective of most hazardous fuel treatments is to reduce the intensity and resulting severity of potential wildland fires (USDA OIG 2016). Some treatments are quantitatively more effective at achieving this objective than others. The protocols developed here offer a means to provide predictions that are objective, consistent, updateable, spatially detailed (30-m resolution), and spatially extensive as a measurable benchmark to characterize changes in fire severity.

Future research

In conducting this study, we identified several refinements that could improve this line of research. For example, our study identified important relationships that are generalizable in terms of broad-scale patterns. However, finer-scale assessments would be necessary to pinpoint exact sites that are at risk of conversion to non-forest. Also, our definition of 'dry forest' and 'forest' in different modules of this study does not account for important attributes in terms of ecosystem function, ecosystem services, and fire regime characteristics. Specifically, we included vegetation types such as pinyon-juniper woodland and ponderosa pine forest in the 'dry forest' class; future efforts could separate these into, for example, 'very dry forest' and 'dry forest'. Efforts to improve fire severity models would improve maps depicting the probability of stand-replacing fire. This is especially needed in ecoregions in California where some of our models did not perform well. We produced models for each ecoregion to describe stand-replacing fire, and consequently, comparing predictions among ecoregions is problematic. Improving models to facilitate comparisons among ecoregions would be a valuable improvement. Lastly, incorporating information on the probability of fire occurrence would improve estimates of which areas are at risk of fire-facilitated conversion to non-forest.

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Appendix B: List of Completed/Planned Publications and Products

1. Articles in peer-reviewed journals:
   - Sean A. Parks, Solomon Z. Dobrowski, John D. Shaw, and Carol Miller (2019). Living on the edge: trailing edge forests at risk of fire-facilitated conversion to non-forest. *Ecosphere* 10(3):e02651.
   - Sean A. Parks, Lisa M. Holsinger, Carol Miller, and Marc-André Parisien (2018). Analog-based fire regime and vegetation shifts in mountainous regions of the western US. *Ecography* 41:910–921.
   - Sean A. Parks, Lisa M. Holsinger, Matthew H. Panunto, W. Matt Jolly, Solomon Z. Dobrowski, and Greg K. Dillon (2018). High-severity fire: Evaluating its key drivers and mapping its probability across western US forests. *Environmental Research Letters* 13:044037.
   - Sean A. Parks, Matthew H. Panunto, and Solomon Z. Dobrowski (2018). What drives low-severity fire in the southwestern USA? *Forests* 9:165.

2. Technical reports: NA

3. Textbooks or book chapters: NA

4. Graduate thesis: NA

5. Conference or symposium proceedings scientifically recognized and referenced: NA

6. Conference presentations:
   - Sean A. Parks, Lisa M. Holsinger, Matthew Panunto, W. Matt Jolly, Solomon Z. Dobrowski, and Greg Dillon (2018). *High severity fire: evaluating its key drivers and mapping its probability across western US forests.* Presented (oral) at the Fire Continuum Conference. Missoula, MT.
   - Sean A. Parks, Lisa M. Holsinger, Carol Miller, Marc-André Parisien, Solomon Z. Dobrowski, and John T. Abatzoglou (2018). *Fire regime shifts under climate change depend on the timeframe and ecological context.* Presented (oral – invited) at the Fire Continuum Conference. Missoula, MT.
   - Sean A. Parks, Marc-André Parisien, Carol Miller, and Lisa Holsinger (2016). *Climate-induced fire regime shifts in the mountains of the western US*. Presented (oral) at the Southwest Fire Ecology Conference. Tucson, AZ.

7. Posters: NA

8. Workshops: NA

9. Field demonstrations/tour summaries: NA

10. Website development:
    - https://www.frames.gov/NextGen-FireSeverity. This website, built and hosted by Fire Research and Management Exchange System (FRAMES), provides links to download gridded, geospatial datasets depicting the probability of stand-replacing fire. See "High-severity fire: Evaluating its key drivers and mapping its probability across western US forests" published in *Environmental Research Letters* for more

information. Official metadata for these geospatial layers is located here: https://www.fs.usda.gov/rds/archive/Product/RDS-ext-2018-0006/.
- These geospatial datasets have also been added to the Forest Service ArcGIS Server: https://apps.fs.usda.gov/fsgisx01/rest/services/RDW_Wildfire/RMRS_NextGenerationFireSeverityMapping/ImageServer.

11. Presentations/webinars/other outreach/science delivery (all presentations and webinars delivered by Sean Parks, unless otherwise stated):
- *Modelling and mapping the potential for stand-replacing fire in the Southwest and beyond* (2018). **Webinar** on October 10, 2018 hosted by the Southwest Fire Science Consortium.
- *Climate change, fire, and the potential for type conversion in the Southwestern US* (2018). Presented (**oral presentation**) to several audiences in New Mexico during the week of September 10, 2018. This series of talks was intended to summarize the findings of the overall study to managers in the southwestern US. Audiences included:
  - ➢ Santa Fe National Forest, Santa Fe, New Mexico
  - ➢ Carson National Forest and New Mexico Highlands University, Las Vegas, New Mexico
  - ➢ Gila National Forest, Silver City, New Mexico
- *A world in pixels: How new research if helping predict the probability of high-severity fire* (2018). Science you can use (in 5 minutes) **bulletin** produced and distributed by the Rocky Mountain Research Station.
- *Next generation fire severity modelling and mapping* (2018). Presented (**oral presentation**) at the USFS Northern Region University. Missoula, MT.
- *Short- and long-term responses of fire regimes to a changing climate* (2017). Presented (**oral presentation**) at the Southwestern Regional Watershed, Air, Ecology, Climate Change, and Invasive Species Workshop. Flagstaff, AZ.
- *Short- and long-term responses of fire regimes to a changing climate* (2017). Presented (**oral presentation**) at the Missoula Fire Sciences Laboratory weekly seminar.
- *Next generation fire severity modelling: generating 'wall-to-wall' fire severity predictions* (2017). Presented (**web-based presentation**) to the Wildland Fire Management – Research, Development & Application team.
- *How will climate change affect fire regimes in the western US?* (2016). Presented (**webinar**) at the First Friday All Climate Change Talks (FFACTS).
- *Analog-based predictions of western US fire regimes under climate change* (2016). Presented (**web-based presentation**) to fire managers in Alaska from USFS, NPS, USGS, and USFWS.
- *Quantifying the risk of fire-facilitated transition to non-forest in California and the Southwest* (2016). This informal **roundtable discussion** was geared towards managers and intended to describe the rationale and methodology of the project, show preliminary results, and receive feedback pertaining to the study design and objectives. Approximately eight USFS managers/employees attended this discussion that was held in conjunction with the Southwest Fire Ecology Conference in Tucson, AZ.